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Applicability of Biofiltration to Indoor Air Control in a Confined Space

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ABSTRACT

The present study aimed to evaluate the applicability of biofiltration to indoor air purification in a confined space for the longevity of human life and to support green activities. Currently, research on indoor air biofiltration in confined spaces is limited and ambiguous. This paper, on the other hand, provides a conceptual model that incorporates the factors to be considered while designing an indoor biofilter. The evaluation was focused on predicting the removal of certain target gaseous compounds that are generated from human bodies and from activities in confined spaces. The target gases include ethylene, ammonia, carbon monoxide, carbon dioxide, water vapor, and oxygen. A major target for the biofilter design should be the ability to completely remove ammonia gas from the confined space, due to its high generation rate ($>$350 mg/day/personnel) and high toxicity (over 7 mg/m^3). Carbon monoxide is also a dangerous gas in that it is easily generated via incineration and is highly toxic at over 10 mg/m^3; however, its removal using biofiltration is difficult.

Key words : Biofiltration, Indoor air, Mathematical model, Confined space

Introduction

Human living in a confined environment has been planned as long-term missions in cabin structures in deep sea or another planet as Mars and the moon. One of the most typical examples may be ALS (Advanced Life Support) system which provides a confined environment for human living in space [1,2]. During the proposed missions, significant amounts of gaseous trace contaminants may be generated and accumulated from equipment off-gassing, human metabolism, waste treatment, and plant growth. Previous studies predicted the existence of gaseous contaminants and their generation rates in the ALS cabin air [1,3]. Table 1 shows the generation data for oxygen and the most significant gaseous contaminants possibly occurring inside of the cabin [1,3]. Here, a long-term mission set i.e. 180-day mean concentration below which crew members can maintain a healthy condition in the cabin structure for the long-duration [1,3]. The SMAC (Spacecraft Maximum Allowable Concentrations) for a compound is defined as the highest concentration allowed for human exposure in the cabin. The mean rates 1 and 2 refer to the average rates of contaminant generation from crew members and the cabin structure, respectively [1]. In this case, the sizes of crew and the cabin mass are assumed to be six people and 71,000 kg, respectively [1,3]. The negative sign in the mean generation rate of oxygen means consumption by human respiration.

In order for indoor air purification, biofiltration has been considered in a large-scale cabin structure that produces various organics. However, few studies were addressed in detail for prediction of applicability of biofiltration based on mathematical modeling. Therefore, this study focuses on evaluation of applicability of a biofilter for indoor air purification in a confined structure, through prediction of removal of the gaseous compounds generated in the cabin. Also, this study would

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Table 1. Generation rates and physico-chemical properties of contaminants in ALS cabin air (Perry, 1995; NASA, 2004)

Compound name	Chemical formula	MW (g/mol)	SMAC (mg/m^3)	Mean rate 1 (mg/d-CM)	St. Dev. 1 (mg/d-CM)	Mean rate 2 (10^{-3} mg/d-kg)	St. Dev. 2 (10^{-3} mg/d-kg)
Ammonia	NH_3	17	7	350	1.36	0.0411	0.0425
Formaldehyde	CH_2O	30	0.056	0.167	0.264	0.0000174	0.0000267
Carbon Monoxide	CO	28	10	13.8	3.74	1.37	0.000658
Methane	CH_4	16	3800	234	94.7	0.543	0.000096
Ethylene	C_2H_4	28	240	–	–	–	–
Carbon Dioxide	CO_2	44	13,000	998,000	–	–	–
Oxygen	O_2	32	–	−835,000	–	–	–

provide review and discussion about which factors should be considered in the design of ALS biofilter.

Materials and Methods

The prediction of indoor biofiltration performance in a confined cabin should start by considering several factors. First, it is assumed that the inlet/outlet airflow and the size of biofilter media bed need to be properly designed to meet the NASA standard for air quality in the ALS system. The liquid recirculation rate must be designed sometimes along with the gas properties and media characteristics. Oxygen consumption by aerobic biodegradation and subsequent carbon dioxide generation also need to be assessed.

The second point is the ALS Equivalent System Mass (ESM) which was derived to limit the total space and weight of the ALS cabin to save energy, especially concerning when the structure needs movement or traveling as well as habitation in a long distance. For example, NASA ALS suggested an equation to find ESM as follows:

$$Total\ mass = M + V \times V_{eq} + P \times P_{eq} + C \times C_{eq} + CT \times D \qquad (1)$$

where M and V are the mass and volume of the system, respectively. P and C are the power and the cooling requirement exerting on the system respectively. CT and D mean the crew time requirement and duration the mission segment for the system, respectively. The constants of V_{eq}, P_{eq} and C_{eq} represent the mass equivalency factors for system volume, power and cooling, respectively. The unique point of this equation is that all of cost for the indoor air biofilter can be transformed into an equivalent mass value. The total mass as a result of the calculation should be as low as possible. Unfortunately, this study would not address all the four terms to suggest a resultant value on the total system mass. This study only considers the volume and mass of the media and discuss other two terms qualitatively.

Finally, various kinds of contaminants may exist in the confined cabin as well as ethylene or ammonia, and may pass through the media in the indoor air biofilter. Table 1 includes some of potential air contaminants released in the ALS cabin. Additionally, there are about 100 compounds listed as gaseous trace contaminants possibly generated in the ALS cabin [1,3]. SMAC is very important, because it is the criteria for determining desirable indoor air purification levels by biofiltration operation. The contaminants have various characteristics on generation rates, toxicity, solubility, and microbial degradability, which influences their transport and fate in the bioreactor. The compounds may include ethylene, ammonia, carbon dioxide, water vapor, and other trace chemicals.

Results and Discussion

The design and operation of biofiltration highly depend on contaminant generation, and concentrations in the cabin. The inlet airflow into the biofilter should be selected so that concentrations of the major contaminants do not exceed hazardous thresholds for the crewmembers. The one-box model [4,5] which assumes that the cabin air is completely mixed was useful for simulating dynamic changes of the mass of gaseous contaminant species i with a concentration of C_i as follows;

$$V\frac{dC_i}{dt} = (G_{iCM} \cdot CM + G_{iS} \cdot SM - L) - Q \cdot RE_i \cdot C_i \qquad (2)$$

where G_{iCM} and G_{is} represents the generation rates based on crew size and total cabin mass, respectively. Q, RE_i and C_i are inlet/outlet airflow rate of the biofilter, removal efficiency of biofilter (= (inlet C_i − outlet C_i)/(inlet C_i) and concentration of gaseous contaminant i in the biofilter, respectively. The schematic diagram for the box model is depicted in Fig. 1. In the study, the number of crew members (CM) is normally six people, and cabin mass (SM) is 71,000 kg (NASA, 2004). The daily cabin air leakage rate (L) is assumed to be 0.05%. The baseline generation rates of trace contaminants [1,3,4] and their physicochemical properties are listed in Table 1 [1,3,4]. The term G_{iCM} and G_{iS} incorporated 1.6 times the standard deviation of each generation rate from human metabolism and cabin structure, respectively. The criterion of the desirable cleaned air is represented as a summation of C/SMAC for each contaminant (C represents the concentration of a contaminant). This means that each contaminant concentration should be far less than the individual SMAC for a single contaminant.

Fig. 2 shows the expected concentration inlet airflow into the indoor air biofilter required to maintain concentration of each contaminant compound below the SMAC during 180 days of operation. The data in the figure were derived from the one-box model under steady state. The predictive concentrations with the SMAC of ammonia implied the inlet airflow to meet the SMAC (7 mg/m^3) should be $200 \times R.E.^{-1}$ L/min in which $R.E.$ means the ammonia removal efficiency of the indoor air biofilter. For that case, the ammonia inlet loading is equal to $1.4 \times R.E.^{-1}$ mg/min for the airflow. Based on the biotic experiment in this study [6-8], the ammonia inlet loading ranged from 0.15-0.35 mg/min, and based on the profile study, the removal efficiencies were close to 100% using 50 cm of perlite media depth for which EBRT is about 30 s.

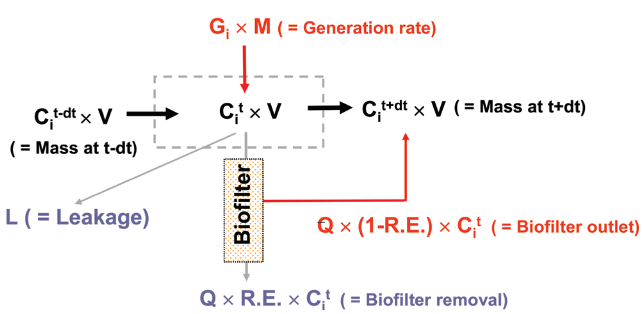

Fig. 1. The schematic diagram of the one box model for ALS cabin with a biofilter.

In contrast, the SMACs of carbon monoxide require a removal efficiency of at least 10% for the given airflow rates. Ammonia biofiltration has been studied and often exhibited a good performance [6-9], but insufficient data exist for biodegradation of carbon monoxide; this needs future studies. The generation of ethylene in the cabin is so small that a low removal efficiency of ethylene may be allowed with respect to the SMAC. This study utilized about 0.25 mg/min of inlet ethylene loading for the biotic experiment. The ethylene removal efficiency was expected to be higher than 50% using perlite biotrickling filters. Therefore, ethylene treatment is not a significant determining factor to design or operate the biofilter, but low levels of ethylene can inhibit plant growth.

The relative humidity in outlet gas is at least 90% during a long time operation of the biofilter. Based on the assumption that the inlet relative humidity is 60%, approximately 50 mg/min of water vapor can be generated by the biofilter. This will be a significant limitation of application of biofiltration to indoor air treatment, unless dehumidification is used to remove the outlet water vapor. The concentrations of many other compounds are less than their SMACs even with low removal efficiency or low airflow rate. VOC compounds such as formaldehyde are easily biodegradable and highly soluble in water [4,10]. Thus, high removal efficiency is expected with the biofilter. As mentioned previously, ammonia and carbon mon-

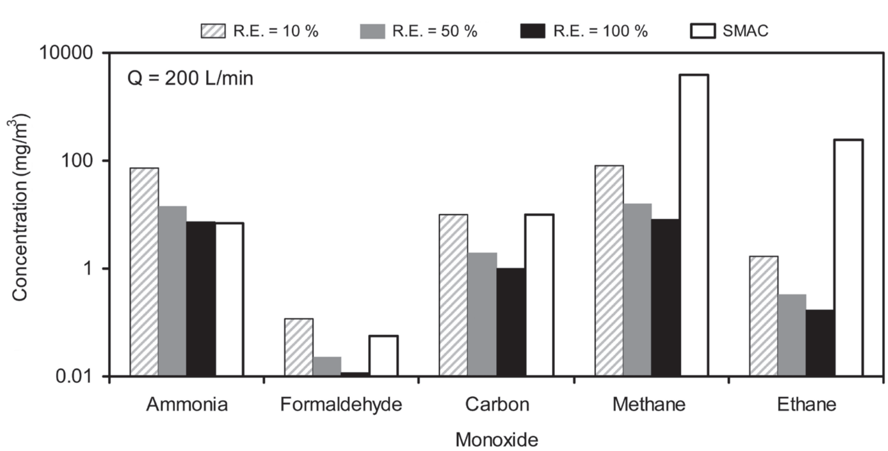

Fig. 2. Predictive concentration and SMAC for each contaminant according to biofilter removal efficiency during 180 days of operation.

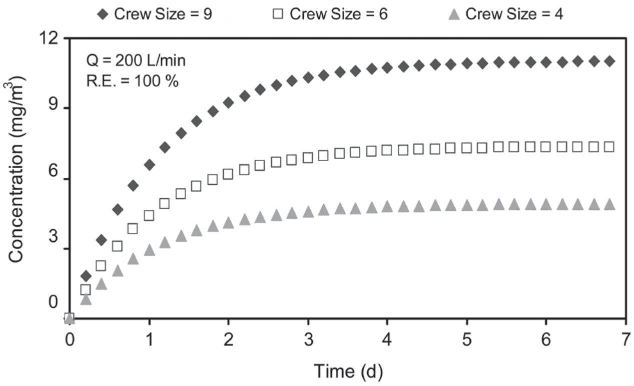

Fig. 3. Ammonia concentrations over a period for 7 days to crew sizes of 4, 6, and 9 persons.

oxide can clearly threaten the health of the crewmembers among the contaminants in Table 1. Additionally, since methane is chemically stable and almost insoluble in water, it is expected to have very low removal efficiencies even at EBRT (Empty Bed Residence Time) of several minutes.

Fig. 3 shows increases in ammonia concentration for 7 days as influenced by crew size, using the one-box model, starting from an initial ammonia concentration of zero. Crew size was varied from 4 to 9 people, but 6 people is the current design value [1]. According to the figure, when crew size is equal to 9, the contaminant concentration is far greater than the SMAC of ammonia, because the ammonia generation rate increases as crew size increases. For a crew size of 9, biofilter airflow should be more than 310 L/min to maintain an ammonia concentration below its SMAC but only 140 L/min is required for a crew of 4 persons. Ammonia generation is not affected by changing cabin structure. Based on the one-box model, biofiltration with 100% removal and 200 L/min of airflow generates cabin air concentration slightly greater than SMAC after 2-4 days. After that, a steady-state condition is reached rapidly. The ammonia concentrations between days 7 and 180 are invariant with 100% of removal efficiency. It is difficult to suggest any values on total mass resulting from ESM calculation using Eq. (1), because many factors included in the equation are still unknown. This study considered each term of the ESM equation. The media volume and mass for the perlite bioreactor in this study were 4 L and 1 kg. The total liquid flowing in the perlite bioreactor in this study was less than 1 L and 1 kg. Based on the inlet gas flow to the biofilter estimated above, the volume and mass should increase by 10-20 times to remove the ammonia effectively, if the EBRT can be reduced to 10-20 s. The total work time for the crew members is 8 hours per day, among which only a small portion of the time can be available for maintenance and operation of the biofilter. Power may be required for pressurizing the inlet gas flow and periodical backwashing of media.

Other discussion on the indoor air biofilter includes additional oxygen consumption, carbon dioxide generation, nutrient utilization, excessive biofilm growth and microbial degradability of contaminants. One crewmember is estimated to daily consume and generate almost 1 kg of oxygen and carbon dioxide, respectively. The total gas generation from other sources inside the ALS cabin is less than 50 g per day, so the concentrations of oxygen and carbon dioxide may not largely be affected by aerobic degradation in the biofilter.

Tchobanoglous et al. [11] reported that microbiological growth requires nutrients such as nitrogen (N) and phosphorous (P), as well as carbon (C). In spite of the additional N provided in the biotic experiment for this study, the ammonia gas daily generated (2 g per day) from the ALS cabin might partially or completely supply the nutrient N for the biofilter. Of course, P or other inorganic nutrients are required to be included in the nutrients. The ammonia loading in the biotic experiment in previous studies [6,8] was quite high compared with carbon loading. Consequently, the nitrification phenomenon was fairly active over all test durations once other conditions such as liquid pH were favorable to nitrification. However, if additional carbon was injected into the biofilter, the nitrifiers will compete with other heterogeneous microbes which need ammonia as nutrients. Most of the gaseous contaminants possibly generated in the cabin, because they are organic and have simple chemical structures, are expected to be biodegradable once they are imbibed in the biofilm phase except for some xenobiotic or chemically stable compounds. However, as stated previously, an important factor to consider is the mass transfer of a contaminant into the biofilm phase [7]. Since wetting of biofilter media is generally a dominant factor, low air/water or air/biofilm partitions as well as high microbial degradation rates are advantageous for facilitating removal of a contaminant.

Lee et al. [9] reported the high sensitivity of biofiltration performance to Henry's law coefficients which ranged from 0.0001 to 50, depending on the compounds. As a consequence, strong hydrophobic compounds as methane and ethylene have low removal efficiencies with the biofiltration. Fortunately, as presented in this study ethylene with its high Henry's law coefficient showed high removal efficiencies under low liquid present in the filter media and overcame the mass transfer limitation. The ethylene was transferred directly from the gas to the biofilm phases. Because biofilm has complex structure and many unknown mechanisms such as enhanced solubility via bio-catalytic reaction [7,12,13], further research should be performed to increase understanding of those phenomena. For the hydrophilic contaminants with low Henry's law coefficients, removal efficiencies usually increase proportionally as their influent loading increase. However, a previous study on the biofiltration of butanol with a low Henry's law coefficient reported that proportional increase of removal according to increasing inlet loadings did not continue as time elapsed. Unexpectedly low removal efficiencies were observed after a certain time [14,15]. Zhu et al. [14] indicated that such phenomena are due to a combination of limiting factors including biodegradability or oxygen availability as well as mass transfer effects represented by the partition coefficients such as the Henry's constants (Henry's constant of oxygen is very high). Further studies should incorporate a high loading of hydrophilic contaminants to observe such combination of limiting factors for contaminants with a high biodegradability and solubility, as well as the mass transfer limitation for hydrophobic contaminants, optimal utilization of nutrients, and interactions of microbes. In future, the model will be compared with experimental data, and recent statistical models will be applied to validate the model [16].

Conclusion

Using the conceptual model, applicability of biofiltration was estimated for indoor contaminant gas removals in a cabin structure to support a long-time human and machine activities. This model study presumed the cabin structure with the indoor air biofilter into two hypothetical boxes with interactions each other. Based on literature review, ammonia was considered as the gaseous compound with the highest generation rate greater than 350 mg/day/CM which is primarily from human bodies. This study chose ammonia gas as the target compound to be eliminated in biofiltration. Ammonia is expected to be well degraded by microbial biofilm but should be carefully treated to maintain a high removal performances. Carbon monoxide is toxic so that it should be eliminated under 10 mg/m^3 but its strong hydrophobicity leads to expectation of low performance in biofiltration. Also, the indoor air biofiltration can provide the troubles in that the outlet air from the biofilter contain additional humidity and carbon dioxide.

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